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## Glacial landsystems, retreat dynamics and controls on Loch Lomond Stadial (Younger Dryas) glaciation in Britain

HANNAH L. BICKERDIKE , COLM Ó COFAIGH, DAVID J. A. EVANS AND CHRIS R. STOKES

BOREAS



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Glacial geomorphology relating to the Loch Lomond Stadial (Younger Dryas) in Britain is used to construct five glacial landsystem models. These landsystems lie on a continuum of increasing ice thickness and decreasing topographic control and typify the principal styles of glaciation during the stadial. The landsystems comprise: the cirque/niche glacier landsystem, the alpine icefield landsystem, the lowland piedmont lobe landsystem, the plateau icefield landsystem and the icecap landsystem. Geomorphological features representing the icecap landsystem are present only at the centre of the West Highland Glacier Complex, which was flanked primarily by satellite alpine and plateau icefields. The cirque/niche glacier landsystem was present predominantly in areas that experienced conditions only marginally favourable for glacier development at peripheral sites. Three styles of glacier retreat are recorded by the geomorphology: active, two-phase and uninterrupted retreat. Of these, active retreat appears to be most widespread within the Loch Lomond Stadial limits. These retreat styles reflect a combination of climatic and topographic conditions, coupled with local factors influencing the preservation of landforms from which retreat dynamics can be inferred. Likewise, the distribution of landsystems was influenced by an interplay between topography and climate, with glacier formation being facilitated in locations where topographical conditions aided in the accumulation of snow. The pattern also supports the existence of previously recognized northward and eastward precipitation gradients across Britain during the stadial.

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The Younger Dryas Stadial, between 12.9 and 11.7 ka, was characterized by an abrupt return to cooler conditions across much of the Northern Hemisphere, following the Last Glacial Maximum (LGM; de Menocal *et al.* 2000; Nakagawa *et al.* 2003; Genty *et al.* 2006; Golledge 2010). In Britain, the period, known locally as the Loch Lomond Stadial (LLS), was characterized by glacier regrowth in the form of a large icefield (over 9000 km<sup>2</sup>) over much of the western Highlands of Scotland, and other satellite icefields, valley and cirque glaciers in upland areas of Scotland, England and Wales (Golledge 2010; Ballantyne 2012). Glacial geomorphology associated with these glaciers has been mapped primarily as localized case studies of specific areas (Sissons 1974; Benn *et al.* 1992; Ballantyne 2002a), producing a fragmented and spatially inconsistent body of research, which has inhibited regional scale analysis of the extent and dynamics of LLS glaciers. Recently, the published literature on the glacial geomorphology of the LLS in Britain was compiled into a GIS database and glacial map (Bickerdike *et al.* 2016). This database has, for the first time, permitted the geomorphology of the total extent of the LLS glaciers to be assessed at scales varying from within individual valleys to across whole icefields. Furthermore, it has facilitated comparison of the geomorphology between different regions and has allowed patterns in the style of glaciation and the nature of retreat of these glaciers to be identified.

This paper uses the landsystems concept to identify the process-form regimes inherent within LLS glacial geomorphology (Evans 2003). Benn & Evans (2010) and Evans (2003) have argued that landforms and sediment assemblages are, in part, influenced by a continuum of glaciation styles and dynamics, which are themselves influenced by the relative importance of topography and thermal regime. Landsystem type is partly governed by the supply and turnover of both ice and debris, which are themselves influenced by climate (Benn *et al.* 2003). Therefore, by mapping landsystems, and using these in combination with process-form models and modern analogues, it is possible to make inferences about spatial and temporal variations in climate at the time of landform formation (Benn *et al.* 2003; Evans 2013). In this context, it should be noted that the timing of the maximum extent of LLS glaciation is controversial and, whilst this paper presents a reconstruction of the maximum extent of the LLS ice masses, chronological control on their termini is extremely limited. Absolute dates suggest that some LLS glaciers reached their maximum extent during the mid-stadial (e.g. Benn *et al.* 1992; Ballantyne 2012) or earlier (Bromley *et al.* 2014), whilst others continued advancing until the end of the stadial (e.g. Palmer *et al.* 2010; MacLeod *et al.* 2011; Small & Fabel 2016).

Landsystem models have rarely been applied to LLS landforms and deposits in Great Britain. Hence the aims of this study were to identify the type of glacial

landsystems and retreat styles represented by the LLS geomorphology and to map the distribution of landsystems at a regional scale to determine possible controls on the nature of LLS glaciation across Britain. Specifically this employs the geomorphology compiled by Bickerdike *et al.* (2016) to create a series of glacial landsystem models that incorporate the LLS landform signatures and uses these models to identify the process-form relationships associated with each of these landsystems. The landsystem models are then used to create a first-order classification of the LLS ice masses and to map the distribution of each landsystem type across Britain. This facilitates the identification of the principal glacier retreat styles that characterized LLS deglaciation and the most significant controls on LLS glacier extent, style and dynamics.

## Material and methods

LLS glacial landsystems were identified from the glacial map compiled by Bickerdike *et al.* (2016). The map was examined for recurring patterns of genetically linked landform units, which were then used to identify five landsystem models. In order to map the distribution of each landsystem type, empirically based reconstructions of the maximum extent of LLS glaciation (e.g. Ballantyne 2002a; Benn & Ballantyne 2005; Lukas & Bradwell 2010; Boston *et al.* 2015) were compiled from the literature into ArcGIS and were digitized as polygon features. The landsystem models were then applied to a first-order classification of each individual ice mass, based on both the landforms present within the limits of each polygon and their topographic setting.

Typically, a similar combination of landform units is found in each of the landsystems identified. This is potentially a result of the relatively small scale of the LLS glaciers. The narrow range of landsystems observed probably also reflects the relatively narrow range of topographic and climatic conditions across Britain during the stadial. Consequently, not only is the type of landform unit but also their topographic setting instrumental in classifying the landsystem of each ice mass. For example, sequences of recessional moraines are found in four of the LLS landsystem models proposed here, but their distribution in each is different. In the cirque/niche glacier landsystem, recessional moraines are restricted to the floors of cirques and seldom extend beyond the mouth of the cirque itself (e.g. Sissons 1977; Carr 2001; Bendle & Glasser 2012). In the alpine icefield landsystem, they are found extensively within the valleys (e.g. Ballantyne 2002a, 2007a, b; Lukas & Lukas 2006a, b), whilst in the plateau icefield landsystem recessional moraines extend from the valleys onto the upland plateau surface (e.g. McDougall 2001, 2013; Boston 2012; Boston *et al.* 2015). Likewise, recessional moraines are found on the high ground of the icecap landsystem but, unlike those in the plateau icefield landsystem, these

features are discordant with the underlying topography (Golledge 2007). Thus, it is not only the presence or absence of landform units that informs the landsystem classification of LLS geomorphology, but the distribution of landforms with regards to the glacial limits and underlying relief.

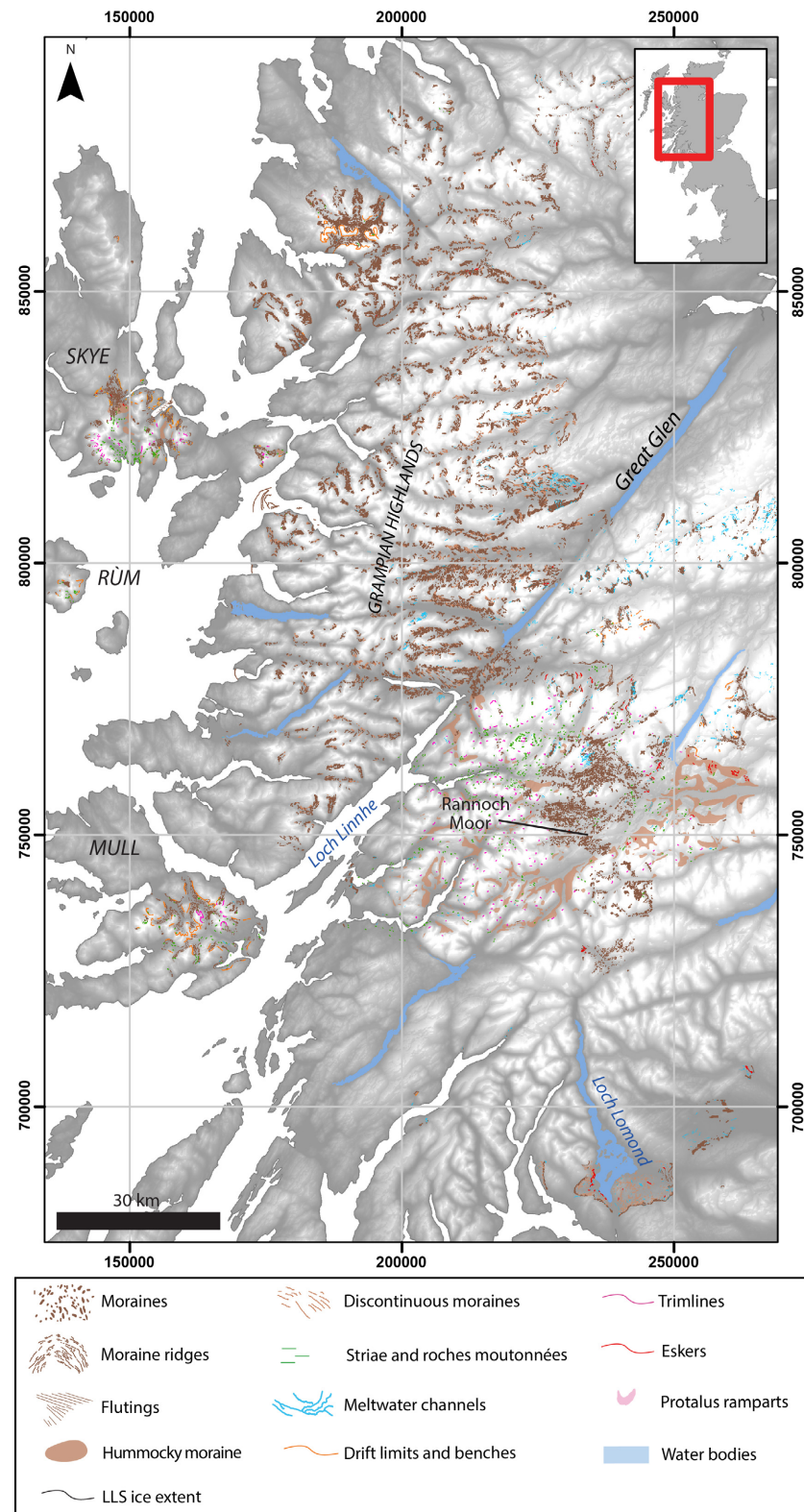
Each ice mass was classified as one of the five landsystem types, depending on which style of glaciation was best represented by the landform assemblages mapped within its limits. This methodology required some generalization of local scale variations between different areas of the same ice mass but, due to the extensive and complex nature of the LLS ice masses, subdivision of ice masses into individual drainage basins was unfeasible. It was assumed that the reconstructions accurately represent the maximum extent of LLS glaciation. However, given the probable asynchronous nature of the LLS glaciers (Ballantyne 2012), it should not be inferred that the glacial configuration or landsystem distribution occurred in a single phase during the LLS. Furthermore, the landsystem types developed time-transgressively both within and between catchments, so that the largest ice masses retreated and thinned to become more topographically constrained throughout deglaciation, transitioning from icecaps to icefields, and then to individual cirque glaciers before the ice ultimately disappeared. In most instances, the clearest geomorphological evidence comprises sequences of recessional moraines on the floors and lower slopes of valleys and is believed to relate to the retreat of the LLS glaciers (Bennett & Boulton 1993a; Ballantyne 2002a, 2007a; Lukas & Benn 2006).

## Results

An example of the LLS glacial geomorphology compiled by Bickerdike *et al.* (2016) is presented in Fig. 1 and serves as an overview of the types of evidence that have informed the five landsystems identified in this paper (Fig. 2). The five landsystems incorporate >90% of all landform signatures. Occasional landform examples that did not precisely accord with the proposed models are few in number and reflect the influence of localized depositional and erosional processes on the geomorphology. Such signatures are classified by Evans (2013) as either intrazonal or azonal.

### *The cirque/niche landsystem*

The cirque/niche landsystem (Fig. 3) is primarily found in locations that were peripheral to the main centres of glaciation during the LLS. Glaciers in such areas were generally present in cirques or topographic hollows, particularly those that faced between north and east (Evans 1994, 2015). The maximum extent of these glaciers is typically demarcated by sequences of recessional moraine ridges (1 on Fig. 3). These features sometimes



*Fig. 1.* Example of the LLS glacial geomorphology compiled by Bickerdike *et al.* (2016). The map is dominated by moraines (brown), particularly the extensive sequences of recessional moraines that are widespread throughout the northern sector of the West Highland Glacier Complex. Satellite icefields formed on the isles of Skye and Mull and on upland areas peripheral to the main ice mass on the Grampian Highlands. British coastline and present-day waterbodies reproduced from Ordnance Survey © Crown Copyright and Database Right 2015. Ordnance Survey (Digimap Licence). GB SRTM Digital Elevation Model from ShareGeo, available at [www.sharegeo.ac.uk/handle/10672/5](http://www.sharegeo.ac.uk/handle/10672/5). Original data set from NASA.



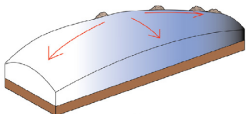
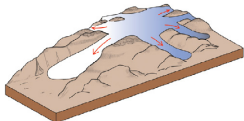
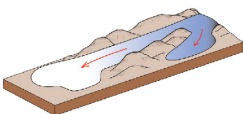
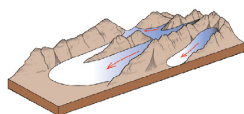
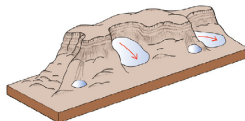
ICECAP	PLATEAU ICEFIELD	LOWLAND PIEDMONT LOBE	ALPINE ICEFIELD	CIRQUE/ NICHE GLACIERS
Glacier size and thickness				
Topographic constraint				
<ul style="list-style-type: none"> <li>- Topographically discordant flow.</li> <li>- Varied topography including alpine-style mountains and topographic basins.</li> <li>- A few nunataks with frost-shattered bedrock on their summits.</li> <li>- Widespread ice-smoothed bedrock including on the high cols and plateau surfaces.</li> <li>- Roches moutonnées on valley floor and lower slopes, which transition to whalebacks at higher elevations.</li> <li>- LGM moraines overridden by LLS flutings, including on the plateau surface.</li> <li>- Asymmetric till deposition within valleys, particularly thick accumulations at the foot of reverse slopes or in topographic hollows.</li> <li>- Sharp-crested moraines along valley floors.</li> <li>- E.g. Glen Lyon and the surrounding valleys, Scotland.</li> </ul>	<ul style="list-style-type: none"> <li>- Topographically concordant flow.</li> <li>- Upland gently undulating plateau of rounded summits, flanked, and sometimes incised, by valleys.</li> <li>- Some nunataks with blockfield developed on their summits.</li> <li>- Ice-moulded bedrock, roches moutonnées and moraines at the heads of valleys.</li> <li>- Substantial networks of ice-marginal meltwater channels, particularly on the plateau.</li> <li>- Sequences of (recessional) hummocky moraines in the valleys.</li> <li>- Some valleys with an absence of evidence.</li> <li>- E.g. Monadhliath mountains, Scotland.</li> </ul>	<ul style="list-style-type: none"> <li>- Topographically concordant flow.</li> <li>- Open and gently undulating, low relief terrain at the foot of glacial valleys.</li> <li>- Mountain ridges and summits exposed above glacier surface to periglacial conditions.</li> <li>- Drift-mantled slopes in middle reaches of valley, though evidence often obscured by afforestation.</li> <li>- Prominent terminal moraine ridges which may enclose areas of chaotic hummocky moraine, kames and kame terraces and eskers.</li> <li>- Evidence of proglacial glaciectonism from the advance of LLS ice over pre-existing deltaic sediments.</li> <li>- Thrust-block moraines and hill-hole pairs, possibly indicating glacier surging.</li> <li>- E.g. the Lomond valley, Scotland.</li> </ul>	<ul style="list-style-type: none"> <li>- Topographically concordant flow.</li> <li>- Alpine-style mountains separated by cols and steep-sided glacial valleys. Well-developed cirques. Some limited plateau areas.</li> <li>- Mountain summits and ridges exposed to periglacial conditions as inferred from blockfields and solifluction features.</li> <li>- Ice-smoothed cols restricted to the icefield centre or low elevations.</li> <li>- Vertical extent of ice marked by trimlines or drift limits.</li> <li>- Transition along valleys from erosional zone in upper valleys (roches moutonnées, striae, flutings) to depositional zone with sequences of recessional moraines and thick till.</li> <li>- Limited evidence of meltwater routing.</li> <li>- E.g. Isle of Mull, Scotland.</li> </ul>	<ul style="list-style-type: none"> <li>- Topographically concordant flow.</li> <li>- Cirques in alpine mountain settings, or the flanks of escarpments marginal to icefield sites.</li> <li>- Blockfields, frost-weathered debris and solifluction features on summits. Mature talus slopes beyond glacier limits.</li> <li>- Glacier development usually restricted to topographically favourable sites with low insolation and/or snow contributing areas up-wind of them.</li> <li>- Single, arcuate terminal moraine ridges often enclosing an area of hummocky drift, or short sequences of recessional moraines.</li> <li>- Protalus ramparts marking the extent of permanent snow-beds.</li> <li>- Mounds and ridges formed from rock-slope failures, which may have a similar appearance to moraine ridges.</li> <li>- E.g. Snowdonia, Wales.</li> </ul>
				

Fig. 2. The landsystem continuum represented by LLS glacial geomorphology. The glaciers decrease in size and thickness from the icecap to the cirque/niche glacier system and become increasingly topographically constrained, as demonstrated by the conceptual flow diagrams. Key characteristics of each landsystem are noted alongside a location of where each landsystem has been observed in Britain.

extend back into the source area of the former glacier, but usually form a belt of moraines near the terminus, or comprise single prominent arcuate terminal moraine ridges. These moraines frequently enclose areas of hummocky drift mounds (2) with no obvious pattern apparent in their distribution within the glacier limits. Other features in proximity to such glaciers include protalus ramparts (3), paraglacial rock-slope failures (4) and relict periglacial features, such as frost-weathered detritus and blockfields (5) on mountain and escarpment summits.

The build-up and movement of ice at these sites was controlled by the underlying topography, with ice flowing from the backwalls of cirques towards the glacier margins. Recessional moraines indicate that, in most instances, retreat was active, at least initially, with glaciers remaining near to climatic equilibrium. Conversely, at sites where single arcuate terminal moraines are found, the glacier probably remained at its maximum extent for a sustained period, before undergoing uninterrupted retreat later in the stadial. Cirques in which recessional moraines stretch to the backwall are less common, although they do occur in some areas, such as Cwm Idwal in Snowdonia, Wales (Bendle & Glasser 2012). However, it is difficult to determine whether the relative scarcity of cirque/niche glacier sites where moraine sequences extend to the backwall results from the dominance of an uninterrupted style retreat in the later stages of deglaciation, or simply reflects that, in

many sites where the floor of the cirque rose steeply to meet the backwall, surfaces were unfavourable for debris accumulation and preservation.

At sites where snow accumulation was insufficiently thick for glacier development, perennial snowbeds formed, over which debris from the cirque backwall or escarpment slid or rolled to produce protalus ramparts. In several locations, such as Fan Hir in the Brecon Beacons, Wales, difficulty in differentiating between single terminal moraines and protalus ramparts arises from their similar morphology (Shakesby & Matthews 1993; Carr & Coleman 2007). Similar difficulties have been encountered when differentiating between glacial deposits and debris ridges formed by paraglacial rock-slope failures, particularly when these occur within cirques (Carr *et al.* 2007; Mills & Lukas 2009). Such rock-slope failures in Britain have been attributed, primarily, to enhanced seismic activity during periods of accelerated glacio-isostatic uplift as the crust responded to removal of the Late Devensian Ice Sheet (Ballantyne *et al.* 2014).

Relict periglacial features are frequently found as components of the cirque/niche glacier landsystem, with frost-weathered detritus and blockfields being present on many summits and mature talus slopes mantling the valley sides. The well-developed nature of such features, in contrast to those in areas thought to have been glaciated during the LLS, has led to them being interpreted as mature features formed by expo-

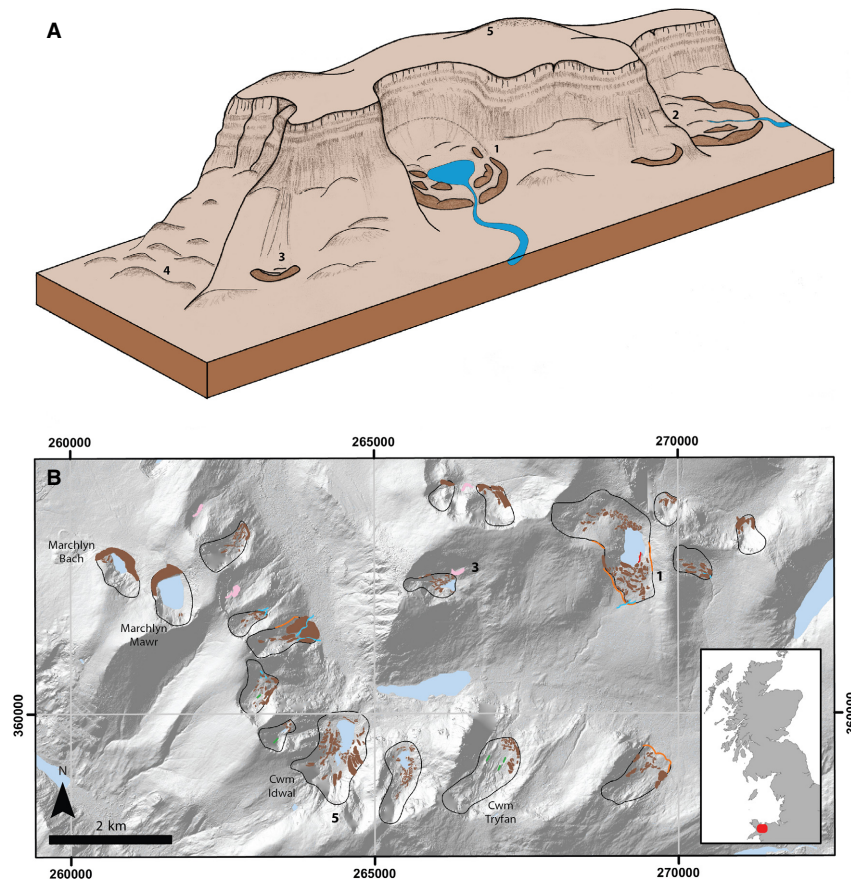


Fig. 3. The cirque/niche glacier landsystem. A. Conceptual model showing the main characteristics of the cirque/niche glacier landsystem, which is found predominantly in areas where conditions were only just above the threshold required for glaciation. 1 = recessional moraines; 2 = hummocky drift; 3 = protalus rampart; 4 = rockslope failure debris; 5 = blockfield. B. Example of the LLS cirque glacier landsystem in Snowdonia, Wales (after Bendle & Glasser 2012). Underlying hill-shaded images were derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.

sure to the severe cold conditions during the stadial (e.g. Curry *et al.* 2007). Consequently, their mutually exclusive relationship with glacial landforms has aided in the reconstruction of the limits of LLS glaciation in numerous studies (Sissons 1974; Benn & Ballantyne 2005; Finlayson 2006). In some instances, however, relict periglacial features occur inside reconstructed limits of LLS glaciation and have been suggested to have been protected beneath cold-based ice (e.g. Boston *et al.* 2015). Given the evidence in many locations for the restriction of ice in the cirque glacier landsystem to topographic hollows (e.g. Carr 2001; Shakesby 2007), it seems unlikely that such areas of cold-based ice would have been present in these locations. Therefore, the use of periglacial features to identify the LLS glacier limits in these localities would appear reliable.

The cirque/niche landsystem is perhaps best exemplified in the mountains of Snowdonia, Wales. In this area a series of 38 LLS cirque glaciers has been reconstructed in topographically favourable sites on the flanks of the mountains (Bendle & Glasser 2012), 18 of which are

shown in Fig. 3B. The geomorphological evidence for these glaciers comprises primarily moraines, ranging from large individual terminal moraines (e.g. Marchlyn Bach and Mawr), to sequences of recessional moraines that extend to the cirque backwalls (e.g. Cwm Idwal). At other sites (e.g. Cwm Tryfan), recessional moraines form a belt near the former glacier terminus but are not present in the middle and upper cirque areas, which are dominated by ice-moulded bedrock. There is a trend in the aspect of these glaciers, with all but two facing between north and east. Beyond the margins of LLS glaciation, protalus ramparts have been identified, either high on the walls of cirques or on the convex flanks of mountains, indicating that perennial snowbeds developed at these sites.

#### *The alpine icefield landsystem*

The alpine icefield landsystem (Fig. 4) represents one end of the mountain icefield landsystem continuum, the other being the plateau icefield landsystem. It is

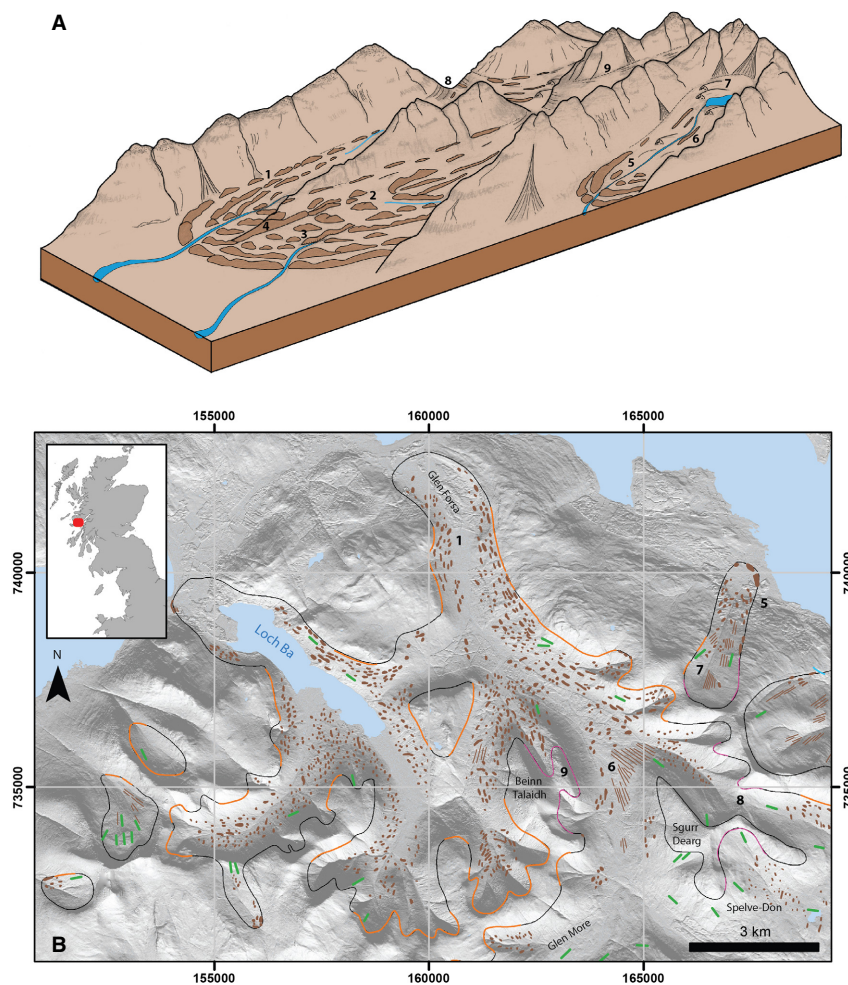


Fig. 4. The alpine icefield landsystem. A. Conceptual model of the alpine icefield landsystem, found in areas of steep alpine topography where interconnected networks of valley glaciers develop. The extent of glaciation is highly influenced by topography with most mountain summits remaining exposed above the ice. 1 = recessional moraines; 2 = chaotic moraine mounds and ridges; 3 = esker; 4 = medial moraine; 5 = restricted belt of end moraines; 6 = flutings; 7 = roches moutonnées; 8 = ice-smoothed bedrock; 9 = periglacial trimline. B. Example of the LLS alpine icefield landsystem on the Isle of Mull, Scotland (after Ballantyne 2002a). Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.

widespread throughout upland Britain in association with LLS glaciation. Areas characterized by the alpine icefield landsystem typically comprise a series of steep-sided, glacial valleys, sometimes connected by cols at their heads, which are separated by arêtes and spurs. Deep, well-developed cirques flank these mountain ridges, whilst plateau surfaces are limited or absent. The alpine icefield landsystem is characterized by sequences of recessional moraines (1 on Fig. 4) arranged in arcuate chains, trending obliquely across the valley floors and lower slopes. Small patches of more chaotically arranged morainic mounds (2) can be observed within these moraine sequences but are not widespread and, likewise, eskers (3) are occasionally present on the valley floors. Medial moraines (4) may mark the confluence of two neighbouring glaciers over a topographic spur and reflect concentrations of supraglacial

debris in the ice, but these features are relatively rare (Bennett 1991). In some areas, particularly cirque-headed valleys, recessional moraines are restricted to a depositional zone near the glacier terminus (5) whilst further upvalley a transition occurs to thin till, sometimes moulded into flutings (6). Nearer the valley heads, erosional features, including roches moutonnées (7), dominate. Ice-smoothed bedrock is frequently present in the upper valleys, including many of the high cols (8), and in many places the maximum elevation of glacial erosion is marked by clear trimlines (9) between the zone of ice moulding on the lower valley sides and periglacial features above.

During the LLS, numerous alpine mountain areas were occupied by interconnected networks of glaciers that developed in the valleys and cirques, with both glacier morphology and debris transport pathways being



highly influenced by the underlying topography (Benn *et al.* 2003). The relief of alpine topography represented in Britain is relatively low compared to that of other alpine mountain regions, such as the Himalaya or Alps, with the valley floors usually only a few hundred metres lower than the mountain summits. Thus, the contribution of supraglacial debris from steep slopes onto these glaciers is comparatively less important (Benn & Lukas 2006).

The restricted patches of chaotic moraine ridges indicate that localized stagnation occurred at the margins of actively retreating glaciers (cf. incremental stagnation of Eyles 1979, 1983; Bennett & Evans 2012), possibly due to the decay of sediment covered ice-cores (Benn 1992). Flutings further upvalley are often found in areas where wet-based ice would have accelerated down steep sections of the underlying topography (Benn 1990; Benn & Lukas 2006). A zone of erosion is generally found at the valley heads, comprising ice-moulded bedrock and roches moutonnées, supporting the assertion that the LLS glaciers were warm-based in their source areas. Likewise, evidence for glacial erosion across the lower cols has been cited as evidence that these were overridden in several instances, allowing individual valley glaciers to coalesce to form an icefield configuration rather than just a series of independent valley glaciers. Trimlines between this ice-scoured terrain and periglacial features have aided in reconstruction of the accumulation areas of glaciers in alpine icefields, particularly where these transition into drift limits in the zone of deposition (e.g. Ballantyne 2002a, 2007a, b; Lukas & Lukas 2006a, b). It is unfortunate that much of the present geomorphological mapping of the West Highland Glacier Complex has focused on the depositional evidence (Bennett 1991; Bennett & Boulton 1993a, b) whilst erosional features remain largely unmapped, inhibiting reconstruction of the vertical limits of much of the icefield.

The Isle of Mull provides a good example of the geomorphology of the alpine icefield landsystem, as shown in Fig. 4B. The extents of the Ba and Forsa glacier lobes are marked by a near-continuous spread of clear recessional hummocky moraines from the terminus to the upper cirques, indicating that these glaciers remained close to climatic equilibrium throughout deglaciation (Ballantyne 2002a). Conversely, much of the area occupied by the Spelve-Don glacier is free of recessional moraines, suggesting that retreat of this lobe was largely uninterrupted until it reached the high cirques where the presence of recessional moraines suggests retreat in equilibrium with climatic conditions was re-established (Ballantyne 2002a). The presence of flutings is clearly visible in the cirques that fed the Forsa glacier. In numerous valleys, thick mantles of drift within the LLS glacier limits contrast with drift-free slopes above, allowing the vertical extent of ice to be established. Evidence of ice-scouring is present in the cols that connect the source areas of the Forsa, Glen More and

Spelve-Don outlet glaciers, but it is clear from drift limits and the trimlines that mark the surface of the ice on the slopes of Beinn Talaidh and Sgurr Dearg that most of the mountain ridges and summits remained above the ice surface.

#### *The lowland piedmont lobe landsystem*

The glacial geomorphology of the lowland piedmont lobe landsystem is best represented by the sites where the Lomond and Menteith glaciers terminated (Fig. 5). Although there is insufficient geomorphological mapping for the upper valleys of these glaciers, their termini are well marked in the geomorphological record. The Lomond and Menteith lobes appear not to have produced extensive sequences of recessional moraines (1 on Fig. 5). Instead, their termini are, at least partially, marked by proglacial glaciotectionic landforms (including thrust-block moraines and hill-hole pairs, (2) which appear to be otherwise largely absent from the LLS landform record, with the possible exception of the Spelve-Don lobe on the Isle of Mull (Benn & Evans 1993). The area inside the prominent moraine ridge, which marks the maximum limit of the LLS Lomond glacier (3), is characterized by chaotic hummocky moraine (4), kames and kame terraces (5) and eskers (6).

During the LLS, the Lomond glacier advanced and blocked drainage down the Endrick and Blane valleys, forming proglacial Lake Blane (Evans & Rose 2003a). Sediment exposures at Drumbeg quarry indicate that the Lomond glacier retreated from proglacial Lake Blane, forming an ice-contact Gilbert-type delta before undergoing a significant readvance into the delta (Benn & Evans 1996; Phillips *et al.* 2002, 2003) (Fig. 5). During this readvance, the deltaic sediments were folded and thrust into a series of composite ridges, which were then overridden by the Lomond glacier, leading to glaciotectionic disturbance of the upper deltaic sediments and the superimposition of a glaciotectionite and subglacial till above them (Benn & Evans 1996; Evans & Rose 2003b). The outer limit of the Menteith lobe is marked by a large moraine ridge, immediately inside of which sits the Lake of Menteith. These features have been interpreted as a hill-hole pair, where the Menteith glacier excavated marine clays, sands and gravels to form the lake basin and thrust and compressed these sediments to form the neighbouring hill (Wilson 2005; Evans & Wilson 2006). Both hill-hole pairs and composite ridges can be associated with surging glaciers, but neither feature is individually diagnostic of this landsystem (Evans & Rea 1999) because they have also been linked to the dislocation of permafrost by polar and sub-polar glaciers (Evans & England 1991; Evans & Rose 2003b). However, crevasse-fill ridges, which Smith (1993) suggested were present within the Menteith glacier limits, are associated with surging glaciers, as are chaotic hummocky moraine



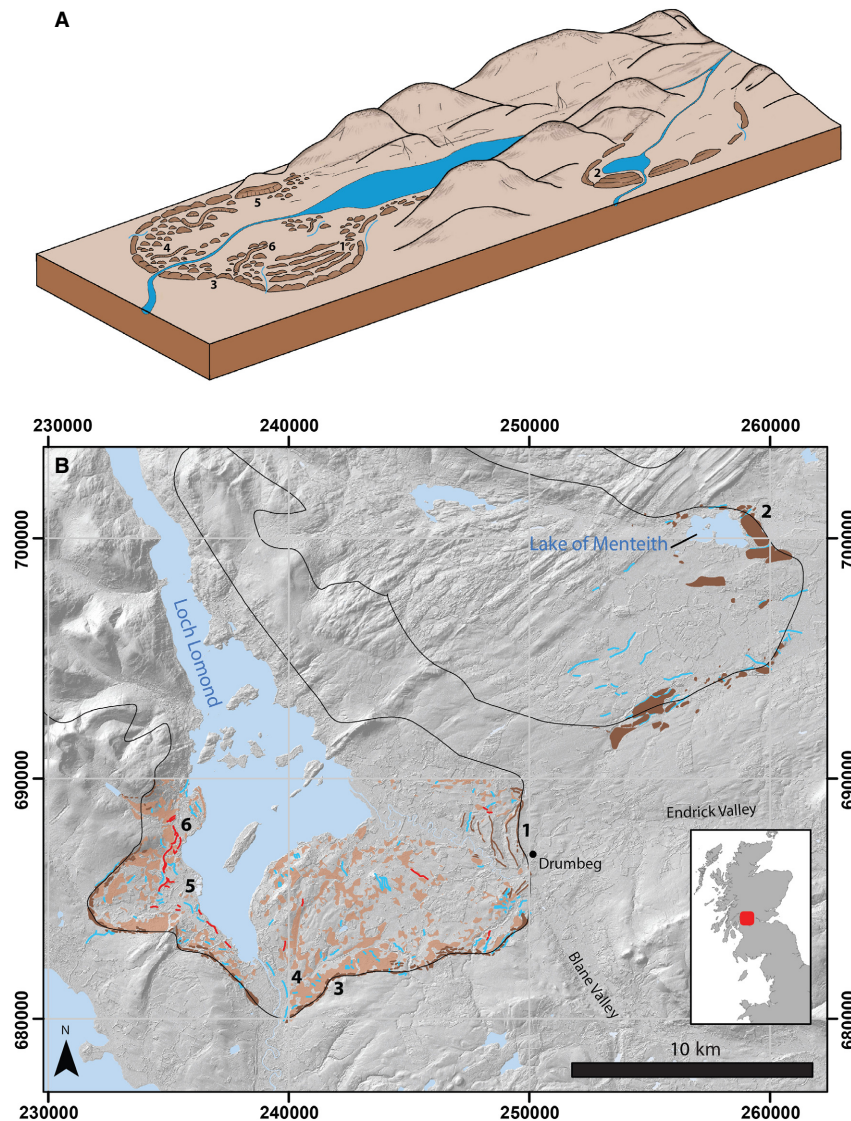


Fig. 5. The lowland piedmont lobe landsystem. A. Conceptual model of the lowland piedmont lobe landsystem. 1 = recessional moraines; 2 = hill-hole pair; 3 = terminal moraine ridge; 4 = chaotic hummocky moraine; 5 = kame terraces; 6 = eskers. B. Example of the LLS lowland piedmont lobe landsystem, the Lomond and Menteith Valleys, Scotland (after Rose 1981; Wilson 2005; Rose & Smith 2008). Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Observation Data Centre. Key as in Fig. 1.

(3) and kames (4), which form during *in situ* stagnation of ice between surges (Evans & Rea 1999); these landforms are present within the limits of the Lomond glacier (Rose 1981) and hence it is possible that the Lomond and Menteith piedmont lobes were prone to surging during the LLS (Evans & Wilson 2006).

#### The plateau icefield landsystem

Plateau icefield landsystems (Fig. 6) are formed by ice masses that are less constrained by topography and more aerially extensive than those associated with alpine icefield glaciation. The topography of these regions is dominated by gently undulating, upland plateaux of

rounded mountain summits, flanked and sometimes dissected by deep glacial valleys. The heads of these valleys may have steep backwalls or may rise gently so that the valley transitions into the plateau surface. The outlet valleys of the plateau icefield landsystem are similar in their geomorphology to those of the alpine icefield. Sequences of recessional moraines (1 on Fig. 6) can be found on the floors and many of the lower valley sides. In some instances, these moraines can be traced back up onto the plateau surface at the valley heads (2), particularly where backwalls are absent. Ice-moulded bedrock and roches moutonnées may also be present at the valley heads, descending from the plateau surface into the valleys. Much of the evidence on the plateau

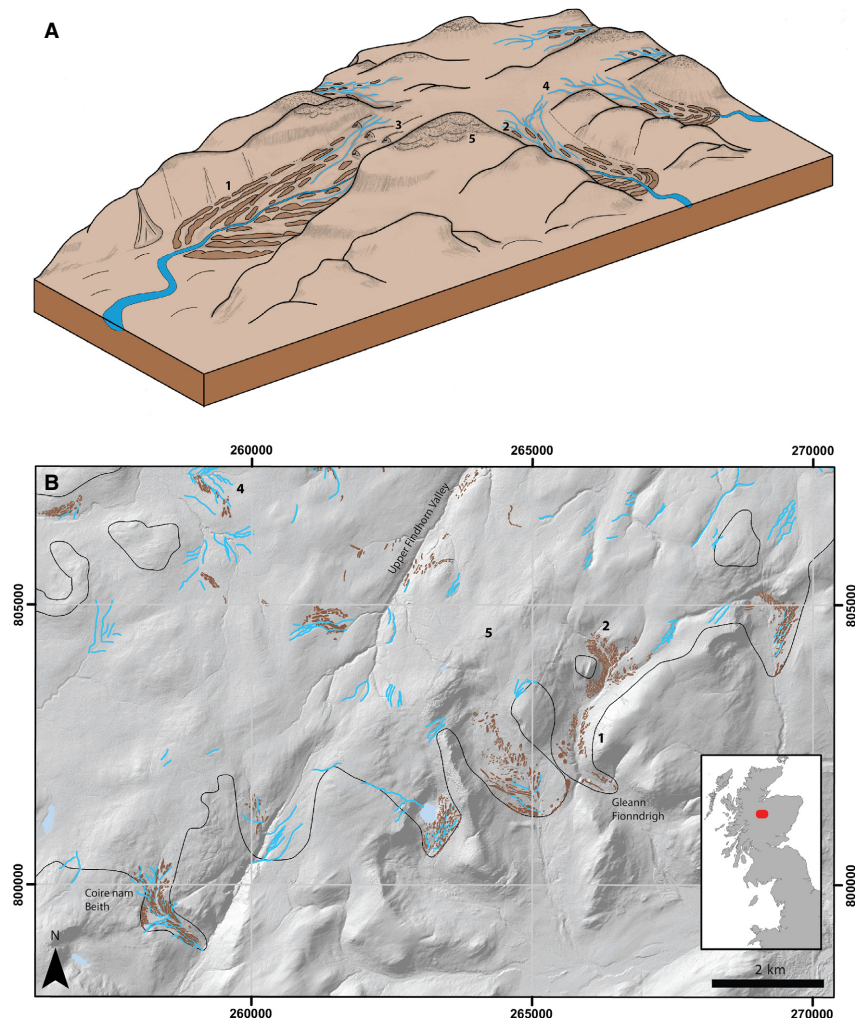


Fig. 6. The plateau icefield landsystem. A. Conceptual model of the plateau icefield landsystem, characteristic of upland areas with gently undulating summits, on which ice accumulated. The plateau was drained by outlet glaciers in the surrounding valleys. 1 = recessional moraines in the valley; 2 = recessional moraines at the valley head, which rise onto the plateau; 3 = ice-moulding and roches moutonnées at the valley head; 4 = ice-marginal meltwater channels; 5 = periglacial blockfields and solifluction lobes. B. Example of the LLS plateau icefield landsystem in the Monadhliath Mountains (after Boston 2012; Boston *et al.* 2015). Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.

surface itself can be subtle, particularly in locations where the plateau surface supports a thick covering of peat. Ice-marginal meltwater channels run between moraine ridges in the valleys but can extend onto the plateau, where they may form extensive networks (4). Periglacial features such as blockfields and solifluction lobes (5) may be present on the higher summits of the plateau.

Accurate mapping of this geomorphology has led to several LLS ice masses, such as those in the English Lake District and the Beinn Dearg massif, being reinterpreted as plateau icefields (McDougall 1998, 2001; Rea *et al.* 1998; Finlayson *et al.* 2011) rather than cirque or valley glaciers (Sissons 1977, 1980a). In some cases, such as in the Lake District, plateau ice provides the only possible accumulation area for glaciers in the surrounding valleys,

the extents of which are well constrained by geomorphology (e.g. Rea *et al.* 1998; Rea & Evans 2003, 2007; McDougall 2013). Such a configuration is further supported by ice-moulding and roches moutonnées at the edge of the plateau where glaciers accelerated as they flowed down steeper slopes.

In light of this evidence, ice within the valleys was probably warm-based on account of the widespread evidence for glacial transport and deposition of debris (Benn & Lukas 2006). In contrast, the presence of ice-marginal meltwater channels on the plateau surface, as observed on many of the plateau surfaces in the Gaick (Sissons 1974) and Monadhliath (Boston 2012), represents meltwater drainage at the margins of the glacier, suggesting that subglacial drainage was inhibited by basal ice being frozen to the underlying bed for at least

some of the melt season (Ó Cofaigh *et al.* 2003; Rea & Evans 2003). Where nested sequences of these meltwater channels are found, these mark successive retreat positions (Dyke 1993; Ó Cofaigh *et al.* 1999; Atkins & Dickinson 2007). The predominance of cold-based, non-erosive ice on the plateau is supported by the presence of periglacial features such as blockfields, including areas that, according to empirically based reconstructions (e.g. Boston *et al.* 2015), were overridden by ice during the LLS. However, the presence of recessional moraines in topographic hollows on the plateau implies that pockets of warm-based ice existed in favourable sites, although these features may have been formed during a late stage of deglaciation when the climate was warmer. Thus, the geomorphological signature of plateau icefields suggests a complex thermal regime, characterized by relatively thin, cold-based ice on the plateau surfaces and thicker, warm-based ice in the surrounding valleys (Boston *et al.* 2015).

The LLS glacial geomorphology of the Monadhliath Mountains (Fig. 6B) is characteristic of a plateau icefield. Clear sequences of recessional hummocky moraines are present on the valley floors and lower slopes and continue up onto the plateau surface (e.g. Coire nam Beith, Coire Fionndrigh and upper Findhorn Valley; Boston 2012). Sometimes these moraines are found in association with ice-marginal meltwater channels (Boston 2012), suggesting that these lobes were either warm-based or polythermal, whereas in other valleys the presence of ice-marginal meltwater channels alone indicates that LLS ice was cold-based (Boston *et al.* 2013, 2015). Areas of blockfield and solifluction lobes are widespread on the plateau, inside the reconstructed limits of LLS glaciation, but are thought to have been protected beneath cold-based, non-erosive ice, rather than exposed as nunataks above the ice surface (Boston *et al.* 2015).

#### *The icecap landsystem*

Unlike other landsystems, many of the elements of the icecap landsystem are discordant with the underlying topography (cf. Golledge 2007). Broad, smooth-topped moraines, which are aligned transverse to ice flow, can be found throughout much of the area (Fig. 7), including the high plateaux, their surfaces having been modified with superimposed lineations (1 on Fig. 7). Moraines are also found on many of the valley floors (2), sometimes misaligned with the surrounding topography, and thick accumulations of till are asymmetrical and deposited on valley sides, particularly where ice flowed obliquely across (3) or up (4) valleys. Evidence of ice-scouring is widespread; roches moutonnées (5) are common on the lower valley sides and a transition occurs to whalebacks at higher elevations (6), but ice-moulded bedrock is present even in the high cols (7). A transition from ice-moulded to frost-weathered debris (8) is apparent on the

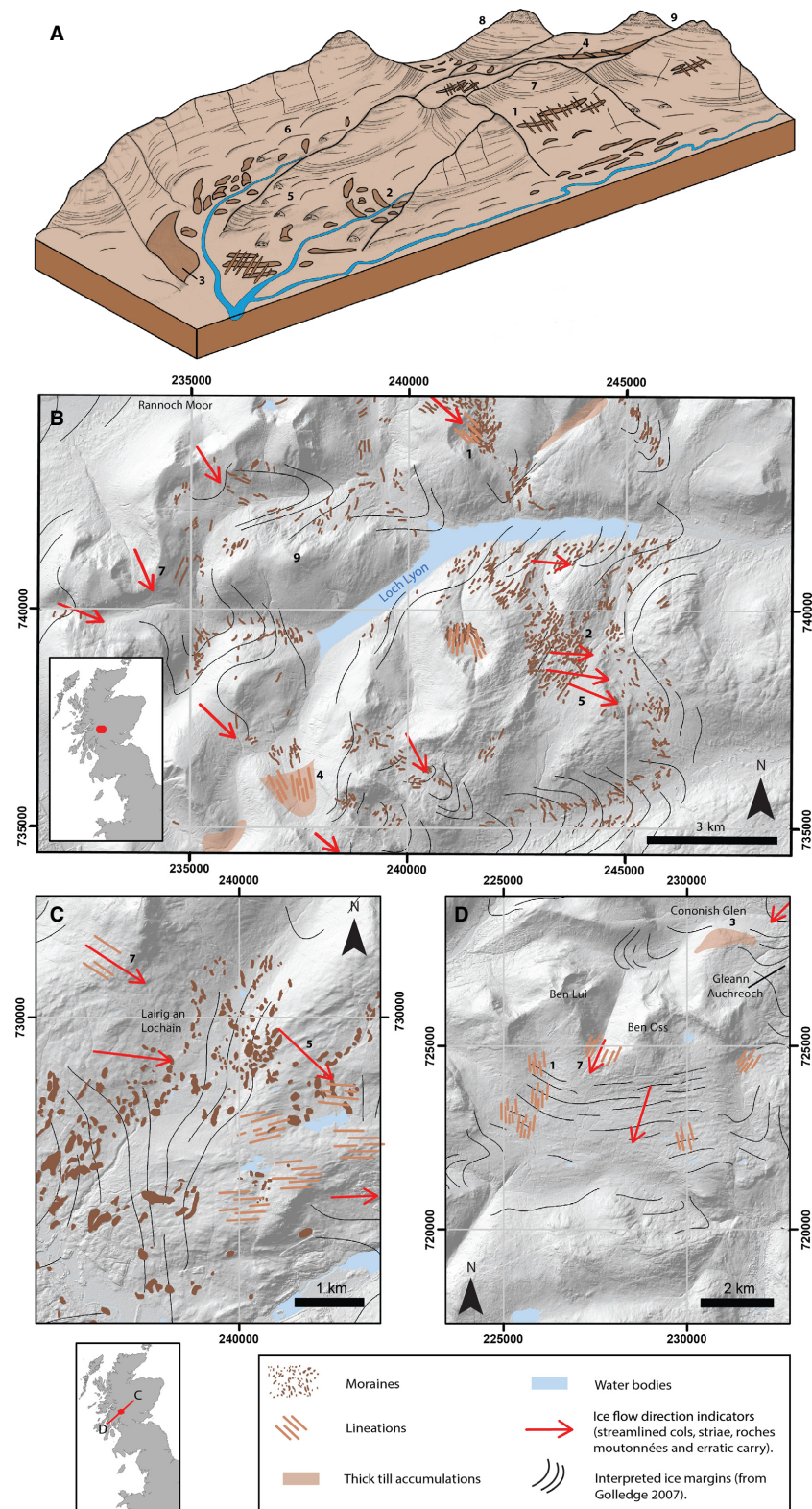
high summits, although Golledge (2006) argued that this transition occurs more gradually rather than as a sharp trimline. Frost-shattered regolith (9) is present on the summits of these hills.

An exemplar of the icecap landsystem is the area between Rannoch Moor and Glen Falloch, where an asymmetrical distribution of deposits is common in numerous valleys. For example, moraines are present on the southern valley slopes and hills of Glen Lyon (Fig. 7B), whilst the northern slopes host only gullied drift (Golledge & Hubbard 2005). Similarly, the moraines in Cononish Glen do not run symmetrically across the valley and those in neighbouring Glen Auchreoch show ice-contact slopes facing downvalley (Golledge 2007), which is impossible to reconcile with glacier flow being controlled by topography. At Lairig an Lochain (Fig. 7C), the ice-marginal positions inferred from the moraine evidence by Golledge (2007) are aligned almost parallel to the valley axis, perpendicular to that expected for a topographically constrained glacier. Transverse moraines overprinted by lineations are particularly well displayed on the upland area south of Ben Lui and Ben Oss (Fig. 7D). Golledge (2006) argued that these have been inherited from an earlier phase of glaciation, probably the Late Devensian, and that the lineations had been superimposed by a minimally erosive LLS icecap; hence they are overridden moraines in our landsystem model. Till cover is generally patchy throughout the area but localized exposures show the preservation of thick till sequences, particularly where the ice flow was not controlled by the underlying topography, such as where it flowed against reverse slopes or obliquely across valleys (Golledge 2007). Like the moraine evidence, this supports the presence of a LLS icecap where flow direction was governed by the ice surface slope, rather than by the underlying relief. Evidence of ice-moulding in the high cols between the mountain summits is displayed in the upland area northwest of Loch Lyon, above Lairig nan Lochain and between Ben Lui and Ben Oss (Golledge 2007). This confirms that LLS ice was sufficiently thick over these sites to continue modifying the ice-moulded surfaces that were abraded by the Late Devensian Ice Sheet, or to at least protect them from modification by severe periglacial conditions during the LLS.

#### *Spatial patterns in the distribution of landsystems*

The glaciers that comprise the cirque/niche landsystem were highly topographically constrained, and thereby constituted discrete ice masses (red on Fig. 8). This landsystem is found primarily around the peripheries of other larger ice masses, at favourable topographic sites where conditions were not conducive for the development of valley glaciers. Suitable locations include topographic hollows or sites in the lee of escarpments, which were protected from insolation or nourished by addi-





*Fig. 7.* The icecap landsystem. **A.** Conceptual model of the icecap landsystem, found at the centre of the main LLS ice mass. 1 = pre-LLS moraines overridden by LLS-aged lineations; 2 = moraines in valleys aligned discordant to topography; 3 and 4 = thick accumulations of preserved till; 5 = roches moutonnées; 6 = whalebacks; 7 = ice-moulded bedrock in the high cols; 8 = transition from ice-moulded bedrock to frost-weathered debris; 9 = solifluction features and frost-weathered regolith. **B–D.** Examples of the LLS icecap landsystem in the vicinity of Rannoch Moor/Glen Lyon, Lairig an Lochain and Ben Lui-Ben Oss, respectively (after Gollidge 2007). Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.



tional windblown snow (e.g. the Outer Hebrides, Skye and Mull icefields are flanked by smaller cirque glaciers). This landsystem becomes progressively more common with distance away from the centre of glaciation in the West Highland Glacier Complex. Glaciation was exclusively of this type in the uplands of Galloway in Scotland, the Pennines in northern England, and both Snowdonia and the Brecon Beacons in Wales. Likewise, glaciation on the Orkney Isles, Scotland, comprised only two small cirque glaciers during the stadial.

The alpine icefield landsystem was widespread in Scotland during the LLS, and covers the greatest combined area (Fig. 8). Clear examples are represented by the satellite icefields on upland areas around the flanks of the West Highland Glacier Complex (Golledge 2010). Substantial alpine-style icefields occupied the upland areas of the isles of Skye and Mull with networks of valley glaciers fed from accumulation areas in cirques and upper valleys (Benn *et al.* 1992; Ballantyne 2002a). The steep nature of the underlying topography inhibited accumulation of ice on the summits themselves and ice drained away from prominent topographic barriers. Smaller alpine icefields were nourished on the isles of Lewis, Harris, Rùm and Arran, some of the outlets of which extended beyond the current coastline. On the mainland, an icefield formed on the Applecross Peninsula. Although previous studies have referred to the glaciation of plateaux in this area during the LLS (Jones 1998), reconstructions by some authors (Robinson 1977, 1987; McCormack 2011) indicate that the valley glaciers were connected over a col but that the majority of the plateau areas were exposed beyond the glacier limits. To the north of the West Highland Glacier Complex, a substantial alpine icefield developed in the mountains of Sutherland (Lukas & Bradwell 2010), the valleys of which are dominated by extensive sequences of hummocky moraine (Benn & Lukas 2006; Lukas & Benn 2006). The same landsystem is present in the West Drumochter Hills.

The alpine icefield landsystem is also represented by the geomorphology of the northern sector of the West Highland Glacier Complex, between Loch na Sealga and the Great Glen (Fig. 8A). The terminology used for the ice mass in this area has alternated between 'icefield' (Bennett & Boulton 1993a; Ballantyne 2012) and 'icecap' (Bennett 1991; Bennett & Boulton 1993b). This is largely because the vertical extent of these glaciers is poorly constrained. The majority of field mapping to date has concentrated on valley-confined geomorphology (Bennett 1991; Bennett & Boulton 1993a, b) and little evidence has been presented from which former ice thickness can be inferred. However, although the majority of the evidence was formed during deglaciation, the signature of retreat in these valleys contrasts starkly with that from the sector of the ice mass south of the Great Glen. The majority of valleys in the northern sector are dominated by sequences of recessional hummocky

moraine formed during deglaciation, indicative of active retreat continuing until the late stages of deglaciation, with glaciers retreating back towards decay centres on the northern and northeastern faces of mountain ridges (Bennett & Boulton 1993a). This retreat pattern indicates a strong topographic influence on the retreat directions of these glaciers, suggesting that an alpine icefield landsystem most accurately reflects the style of LLS glaciation in this area. Furthermore, numerical modelling by Golledge *et al.* (2008) produced an ice mass that closely matched the lateral extent of LLS glaciation, as indicated by empirical evidence, the northern sector of which appears to have contained more nunataks than the southern sector, again supporting an alpine icefield classification for the northern sector.

Geomorphological evidence for the lowland piedmont landsystem is uncommon and has been mapped in only three locations, including the termini of the Lomond and Menteith lobes at the south of the West Highland Glacier Complex, and (possibly) the Spelve-Don lobe of the Mull icefield. In each of these cases, Gilbert-type glaciomarine deltas formed during the retreat of the Late Devensian Ice Sheet were subsequently overridden by outlet glaciers from LLS icefields. Consequently, these locations show evidence of glaciotectionism, including thrust-block and composite moraine ridges, and features that may indicate the surging of these glaciers during the LLS.

To the east of the West Highland Glacier Complex, the plateau icefield landsystem is represented in the Beinn Dearg, Monadhliath, Creag Meagaidh and Gaick mountains (Sissons 1974; Finlayson 2006; Finlayson *et al.* 2011; Boston 2012). In each of these instances, valley outlet glaciers were fed by ice that had accumulated on the plateau, rather than in cirque or valley head source areas. In the southeast Grampians, a small plateau icefield was nourished on the plateaux above Glen Mark, although given the lack of landform evidence here, the presence of ice was largely inferred from the configuration of glaciers in the neighbouring valleys (Sissons & Grant 1972). Plateau icefields were nourished in the Tweedsmuir Hills and the mountains of the English Lake District, the latter representing the most southerly location in the British Isles to have been extensively glaciated during the LLS. Evidence of a LLS icefield landsystem is present in the Cairngorm Mountains, where Bennett & Glasser (1991) and Sissons (1979a) mapped geomorphological evidence indicative of an alpine icefield but Standell (2014) proposed plateau icefield coverage.

Whilst it seems very likely that the northern sector of the West Highland Glacier Complex was characterized by the alpine icefield landsystem, the best evidence of the icecap landsystem is exemplified in the southern sector of the West Highland Glacier Complex. In the vicinity of Glen Lyon, numerous landsystem elements are indicative of topographically discordant ice flow, including stream-lined bedrock in the high cols, striations, roches mou-

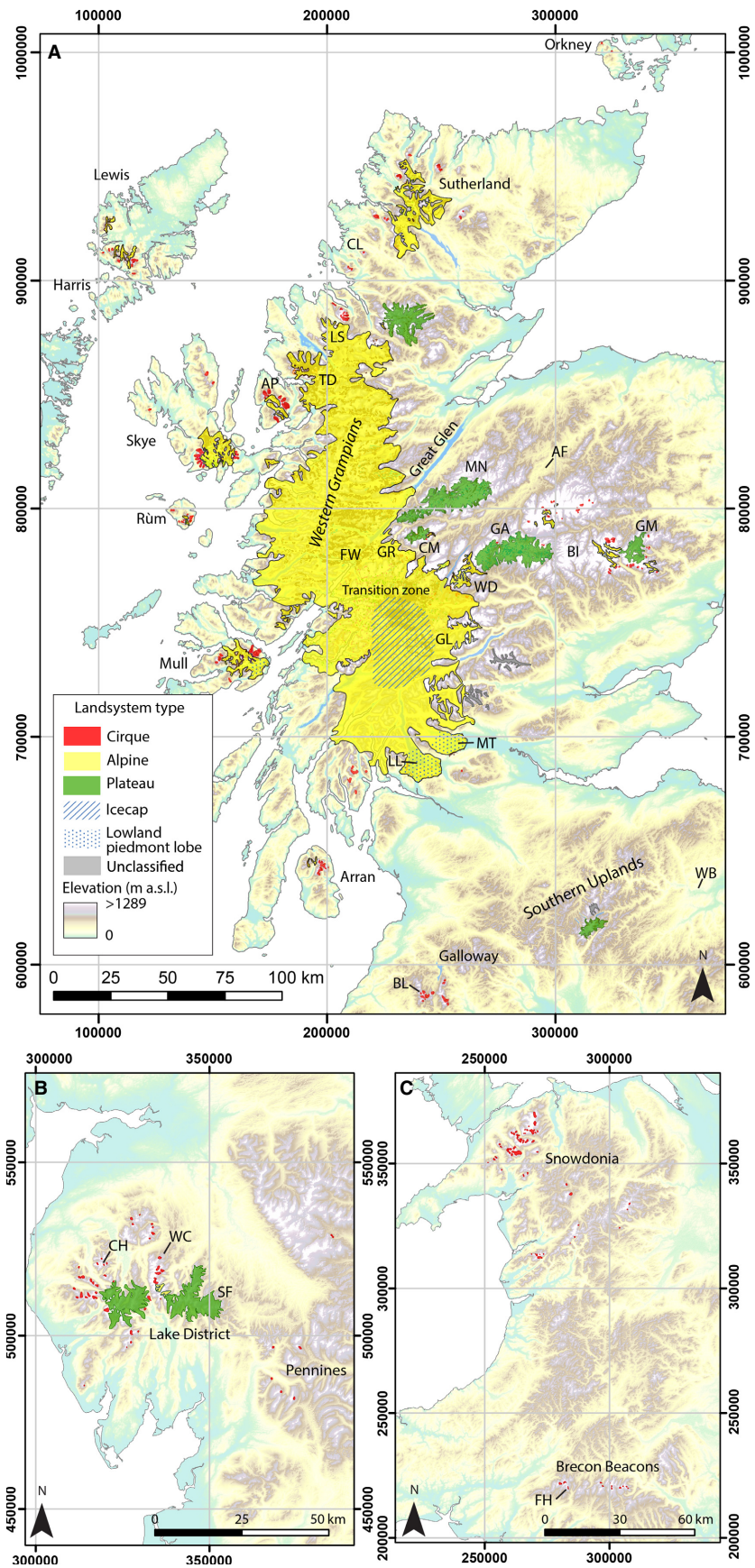


Fig. 8. Spatial distribution of LLS landsystems in Britain. A. Scotland is dominated by the West Highland Glacier Complex, the majority of which comprised an alpine icefield landsystem. The hatched area represents the approximate extent of the icecap landsystem. The limits of this landsystem are uncertain, particularly to the south for which geomorphological mapping is poor, although mapping of the termini of the Lomond and Menteith lobes accords with the lowland piedmont lobe landsystem. CL = Cul Mor; LS = Loch na Sealga; AP = Applecross; TD = Torridon; AF = Abernethy Forest; MN = Monadhliath; CM = Creag Meagaidh; GA = Gaick; BI = Beinn Iutharn Mhor; GM = Glen Mark; GR = Glen Roy; FW = Fort William; WD = West Drumochter; GL = Glen Lyon; LL = Loch Lomond; MT = Menteith; BL = Balminnoch Loch; WB = Whitrigg Bog. B. England hosts evidence of the plateau icefield landsystem nourished in the mountains of the Lake District, flanked by cirque glaciers. CH = Crag Hill; WC = Wolf Crag; SF = Shap Fells. C. The cirque glacier landsystem alone is represented by the LLS glacial geomorphology of Wales, where conditions were only just above the threshold required for glaciation. FH = Fan Hir. British coastline and present-day waterbodies reproduced from Ordnance Survey © Crown Copyright and Database Right 2015. Ordnance Survey (Digimap Licence). GB SRTM Digital Elevation Model from ShareGeo, available at [www.sharegeo.ac.uk/handle/10672/5](http://www.sharegeo.ac.uk/handle/10672/5). Original data set from NASA.

tonées and erratics (Golledge 2007). These features require an ice mass of substantial thickness to have been situated over the area, the radial flow of which could override all but the highest mountain summits. In light of this field evidence and the results of numerical modelling, Golledge & Hubbard (2005) and Golledge (2006) proposed that the upper limit of the LLS icecap must have been at around 900 m a.s.l. This contrasts with the topographically constrained mountain icefield proposed by Thorp (1981, 1984, 1991) for this area. However, as the ice retreated and downwasted, the importance of topography increased. This perhaps explains why the interpreted ice-margin positions in the east are more discordant with the underlying topography than those to the west of Loch Lyon, as by the time the ice margin had reached this area, the underlying topography was exerting more control on the direction of ice flow. Although the Glen Lyon area best exemplifies this style of glaciation, it is possible that ice flow was controlled by the gradient of the ice surface in other locations within the extent of the West Highland Glacier Complex, but that the geomorphological signature of this has subsequently been obscured by increasingly topographically constrained flow during deglaciation. This is an excellent example of intrazonal landsystem signatures.

A slightly different landform assemblage has been observed in the area between Glen Lyon and the Great Glen. Turner *et al.* (2014) observed that within the region of the Great Glen, hummocky moraine, described as irregular mounded terrain ranging between chaotic mounds and nested linear ridges, was found almost exclusively within the Rannoch Moor basin. Both linear elements in the pattern of hummocky moraine mounds around Loch Ba (approximately 5 km north of Fig. 7B), mapped by Wilson (2005), and transverse moraines mapped just east of this by Turner *et al.* (2014), indicate ice flow into the Rannoch Basin from the west and southwest. This evidence accords with the reconstruction of the icecap presented by Golledge (2007), the highest point of which occurs in the vicinity of Stob Ghabhar (approximately 9 km west-northwest of Fig. 7B). In reality this intermediate zone probably represented a transition between the icecap and alpine icefield landsystem styles, becoming increasingly alpine as the ice retreated and downwasted to become more topograph-

ically constrained. It is possible that the complex pattern of hummocky moraine on Rannoch Moor results from the partial preservation of pre-existing moraines that were formed during an early readvance phase of the last British Ice Sheet and were preserved under a LLS icecap, which flowed largely through internal deformation (Golledge 2007).

It is important to note that classification of some areas within the limits of LLS glaciation was inhibited by a lack of detailed geomorphological mapping, for example the valley glaciers flanking the southeastern sector of the Western Highland Glacier Complex. In the northern Tweedsmuir Hills, although moraines have been mapped in several of the valleys, there is insufficient evidence to confidently assign a landsystem type to the features, although Pearce *et al.* (2014) suggested that these valleys were most probably fed by a plateau icefield.

#### Retreat styles

From the geomorphological evidence, it is clear that the retreat style of the LLS glaciers was not uniform across Britain and that variation exists within each of the landsystem models. Hummocky moraine is extensive within the limits of LLS glaciation, to the degree that it was previously considered to be diagnostic of glaciation during the period (Sissons 1974). Sissons's (1961) suggestion that these features resulted from widespread stagnation of ice during the phase of rapid warming at the end of the LLS has been largely superseded by a model of recessional moraine construction by actively retreating glaciers (Bennett 1991; Bennett & Boulton 1993a, b; Benn & Lukas 2006; Lukas & Benn 2006). As each ridge is inferred to have been formed during a minor readvance or stillstand during overall retreat, the position of these ridges can thus be used to reconstruct a series of palaeo ice-front positions, allowing the pattern of retreat to be assessed (Lukas & Benn 2006). By re-examining the LLS geomorphological evidence using this framework, it has been possible to identify three principal retreat styles that characterized LLS deglaciation across Britain. These are termed 'Active retreat', 'Two-stage retreat' and 'Uninterrupted retreat' and are summarized in Fig. 9, which presents conceptual and idealized examples of how each style is represented in the moraine record. Discussion of moraine spacing and sedimentology in



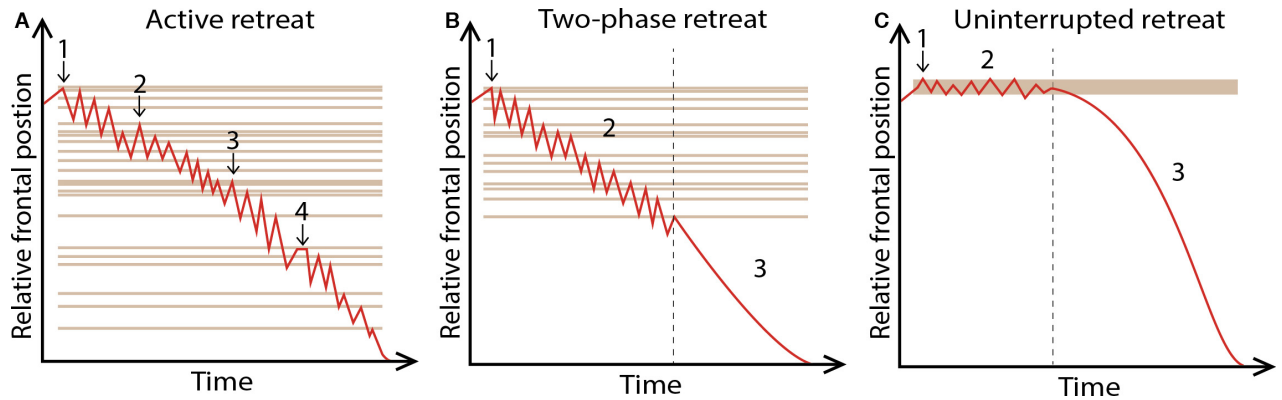


Fig. 9. Conceptual retreat styles of LLS glaciers. Brown horizontal bars indicate the formation of a recessional moraine during a minor readvance or stillstand. A. Active oscillatory retreat throughout general deglaciation. 1 = maximum extent; 2 = readvance beyond the previous retreat position, forming an overridden moraine; 3 = glacier readvance to the same position during multiple readvance phases, perhaps producing a larger, complex push moraine ridge; 4 = period of stability and thus localized stagnation at retreat position. B. Two-phase retreat. 1 = maximum extent; 2 = phase of active retreat (left of the dashed line); 3 = phase of retreat uninterrupted by stillstands or readvances with a consequent lack of recessional moraines formed. C. Uninterrupted retreat throughout deglaciation. 1 = maximum extent; 2 = the glacier oscillates slightly, reaching same margin position during several minor readvances, perhaps facilitating formation of a larger terminal moraine than under scenarios (A) and (B); 3. Phase of uninterrupted retreat (right of the dashed line) from the terminal position and a consequent absence of recessional moraines.

the original publications (e.g. Lukas & Benn 2006) has informed identification of specific stages within overall retreat, as highlighted in Fig. 9.

*Active retreat.* – This is characterized by valleys in which a (near) continuous sequence of recessional moraines stretches from the glacier terminus to the former source area (Figs 9A, 10). The distribution of these moraines indicates that retreat of the glaciers that formed them was interrupted by stillstands and minor readvances

throughout, with the glaciers responding (with minor oscillations) to changes in the climate until very shortly before they disappeared completely. In some cases, such as the icefield in Sutherland, northwestern Scotland, examination of the sediments comprising the recessional moraines indicated that some of these readvances were substantial enough that the glacier readvanced back to, or over, the previous readvance position (Lukas 2005; Benn & Lukas 2006; Fig. 9A: 2 and 3). Where the glacier stabilized at a particular position, localized stagnation

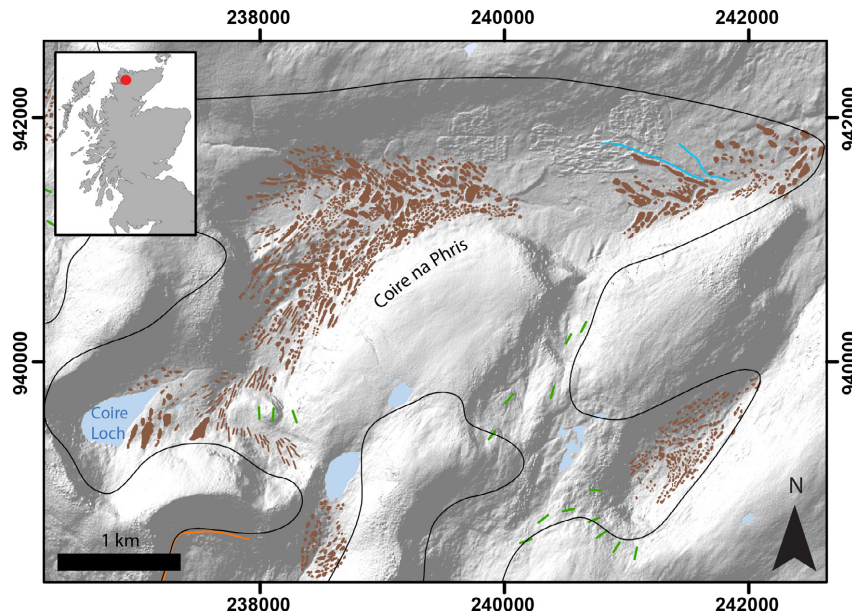


Fig. 10. An example of the geomorphological signature of active retreat until the late stages of deglaciation (from Lukas & Lukas 2006a, b). Recessional moraines form a near-continuous sequence from the terminus of the Coire na Phris glacier, Sutherland, Scotland, to its source area at Coire Loch. This glacier was extremely active, readvancing and retreating rapidly in response to fluctuations in climate during the stadial. Gaps within the sequence indicate periods of uninterrupted retreat. Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.



may have occurred (Fig. 9A: 4). In the case of the Sutherland icefield, glacier size appears to have exerted some control over the frequency of moraine formation. Lukas & Benn (2006) calculated that the smaller glaciers formed moraines on average every 7–23 years whilst the larger ones formed them every 3–11 years, although these calculations assume all glaciers retreated over the same length of time from a mid-stadial maximum extent. This trend is perhaps counterintuitive as changes in climate are often muted by larger glaciers with slower response times (MacLeod *et al.* 2011). This landform signature implies that these glaciers were relatively ‘clean’ and did not support thick mantles of supraglacial debris, which would inhibit rapid glacier response to climate change (Benn & Lukas 2006).

Of the three principal retreat styles discussed here, active retreat appears to have been the most widespread in Britain during the LLS, at least in the areas for which detailed geomorphological mapping exists. This includes the northern half of the West Highland Glacier Complex (Bennett 1991; Bennett & Boulton 1993a), the Sutherland icefield (Lukas & Benn 2006), the Outer Hebrides (Ballantyne 2006, 2007a), Mull (Ballantyne 2002a) and many of the valleys in the Lake District, where recessional moraine sequences continue upvalley and onto the plateau areas (McDougall 1998, 2001).

*Two-phase retreat.* – This retreat pattern (Fig. 9B) has been inferred primarily on the Isle of Skye, Scotland (e.g. Benn 1990, 1992; Benn *et al.* 1992). It refers to scenarios where recessional moraines are largely restricted to the outermost terminal zone of each glacier, even though the

number of ice-front positions represented varies between catchments (Benn 1990). A transition then occurs to terrain indicative of local *in situ* ice stagnation, such as chaotically arranged morainic mounds or thick sheets of irregular drift (Benn *et al.* 1992). Alternatively, the geomorphology upvalley of the recessional moraines may be suggestive of rapid, uninterrupted retreat, for example where the orientation of flutings or erratic dispersal relates to the maximum position of the glacier terminus, indicating that the course of glacier retreat was uninterrupted by subsequent readvances (Benn 1990; Benn *et al.* 1992). It seems likely that the onset of uninterrupted retreat occurred when the ELAs increased during deglaciation, forcing large areas of some icefields (e.g. Skye) to become ablation zones. The reoccurrence of recessional moraines after the onset of uninterrupted retreat occurs in only two locations on Skye, at Harta Corrie and Coire Dubh. Both of these are high cirque sites (Benn 1990; Benn *et al.* 1992), the elevation of which was probably sufficient that, once the icefield had melted, small glaciers in these cirques re-established equilibrium with climate conditions. This would have produced a second phase of active retreat until the ELAs finally rose above even the highest cirques and deglaciation was complete.

Although this two-phase pattern of deglaciation is widespread across the Isle of Skye, it was long considered to have been absent from mainland Scotland (Bennett & Boulton 1993a). However, recent work from Torridon has reconstructed a two-phase deglaciation pattern. In this locality, an abundance of chaotic morainic mounds have been mapped in the area that fed much of this sector

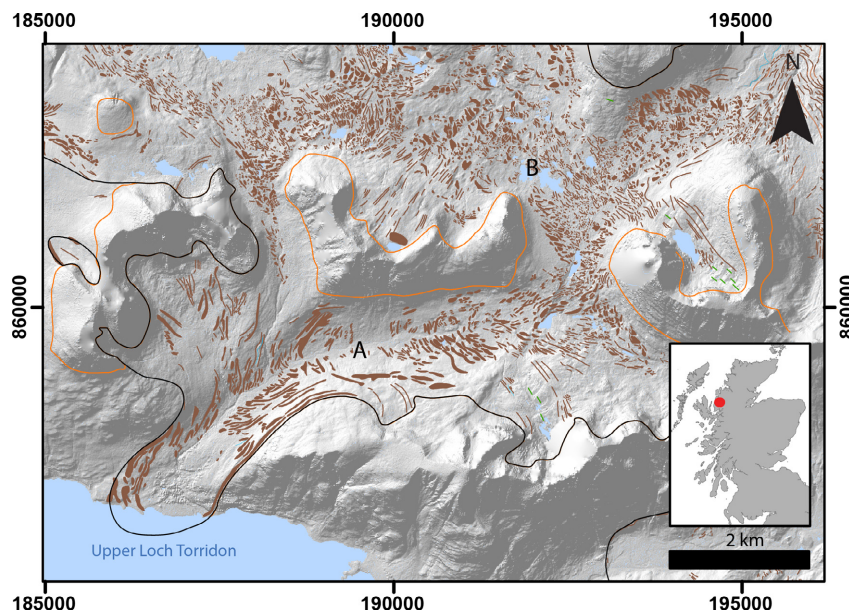


Fig. 11. An example of the geomorphological signature of two-phase retreat (from McCormack 2011). The extent of the LLS glacier that descended from the Torridon icefield into Upper Loch Torridon is marked in its lower reaches by a sequence of prominent recessional moraines (A). This contrasts with the chaotic mounds, indicative of ice stagnation, which are found in its former source area (B). Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.

of the LLS icefield (McCormack 2011; Fig. 11). McCormack (2011) suggested that the transition to stagnation terrain in the form of chaotic debris mounds could possibly be attributed to a high supraglacial debris load that insulated the ice, causing it to become disconnected from the accumulation areas, and thereby inactive. Likewise, although recessional moraines were observed in the upper valleys of some of the glaciers in the West Drumochter Hills, these are largely absent above 550–630 m a.s.l., suggesting that the final stages of retreat were also uninterrupted in this locality.

*Uninterrupted retreat.* – This is rather uncommon and occurred in areas where recession from the maximum ice limit appears to have been largely uninterrupted by stillstands or readvances, as indicated by an absence of recessional moraines. In some cases, the associated geomorphological record takes the form of a large terminal moraine ridge (as described by Sissons 1980a), formed by the glacier oscillating to and from the same margin position (Fig. 9C: 2), inside of which recessional ridges are absent (Fig. 12; e.g. the terminal moraines at Bowscale and Scales tarns (Fig. 12A), and the northeast flank of Crag Hill, Lake District, England; Sissons 1980a). Similar features are found in Wales at Llyn y Fach (Fig. 12B) in the Brecon Beacons and at Melynlyn (approximately 2 km north of Fig. 3B), Snowdonia (Bendle & Glasser 2012). These features are also present at both Balminnoch Loch (Fig. 12C; Cornish 1981) and Cul Mor Assynt (Sissons 1977) in Scotland. Such

features indicate that the glacier remained at its maximum extent for a prolonged period, allowing sufficient debris to accumulate and form a large moraine ridge at the terminus. The absence of moraines inside this outer limit indicates that, once deglaciation commenced, it was uninterrupted by stillstands or readvances. Between the two-phase and uninterrupted retreat styles there are numerous examples of large outer moraines inside of which one or two recessional ridges are preserved (e.g. Wolf Crag in the English Lake District (Sissons 1980a)). The reasons for the tendency for apparently uninterrupted retreat to have occurred only in the relatively smaller palaeo-glaciers outlined above are unclear. Potentially, the evidence could indicate that these small ice masses were indeed incapable of maintaining quasi-stable fronts after the peak of the LLS maximum (uninterrupted retreat). Alternatively, they may have failed to deliver sufficient debris to their margins to form moraines and hence the lack of recessional moraines is a reflection of restricted basin sizes. The palaeoglaciological and palaeoclimatic implications of this landsystem signature require further investigation.

### Controls on LLS extent and retreat style: the relative importance of topography vs. climate

#### *Local controls on moraine formation and preservation*

An assumption in much of the previous mapping of LLS glacial geomorphology is that the distribution of

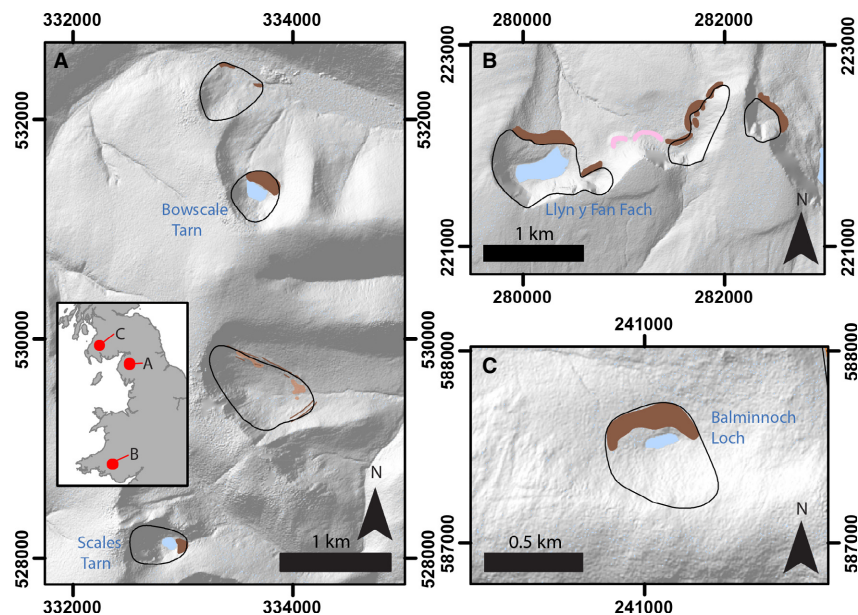


Fig. 12. Examples of the geomorphological signature of uninterrupted retreat at (A) Bowscale and Scales tarns, Lake District, England (from Clark & Wilson 2001; Sissons 1980a), (B) Llyn y Fach, Brecon Beacons, Wales (from Shakesby 2007) and (C) Balminnoch Loch, Galloway, Scotland (from Cornish 1981). In each instance, the maximum extent of the LLS glacier is marked by a single, large terminal moraine, inside of which no recessional moraines are present. Hill-shaded images derived from NEXTMap DSM from Intermap Technologies Inc. provided by the NERC Earth Observation Data Centre. Key as in Fig. 1.

features accurately represents the ice-marginal positions throughout deglaciation, allowing inferences about the palaeoclimate at the time of formation to be made (e.g. Lukas & Benn 2006). However, variations occur in the preservation of geomorphological evidence between adjacent valleys of the same landsystem type, giving rise to intrazonal and azonal land facets and elements (*sensu* Evans 2013) within the five landsystem models described above. For example, of the 53 outlet glaciers from the Monadhliath icefield, morainic evidence is absent from 23 valleys, in contrast to 17 that have clear recessional moraine sequences (Boston *et al.* 2015). Moraines are also largely absent from the valleys of the westward draining lobes of the main West Highland Glacier Complex, in marked contrast to the moraine-filled valleys in the east (Bennett & Boulton 1993a). Similarly, the recessional moraine sequences of the Mull icefield lobes contrast with the terrain occupied by the Spelve-Don lobe (Ballantyne 2002a). In the English Lake District, numerous valleys host impressive LLS recessional moraines and yet some valleys possess little, if any, morainic evidence (McDougall 2001, 2013). Moreover, the signature of plateau icefield glaciation in the Lake District gives way locally to alpine styles of ice cover where the relief is more fretted.

There are several possible reasons for localized gaps in the depositional landform record, relating either to the tendency for glaciers to deposit no moraines, or the poor preservation potential of moraines during, and subsequent to, deglaciation. In the Monadhliath Mountains, Boston *et al.* (2015) proposed that this was influenced by factors such as low debris turnover and availability, uninterrupted retreat, and differences in bed topography. A low turnover of debris accords well with the notion of cold-based ice forming a component of plateau icefields. However, this does not account for the lack of moraines associated with the western outlets of the West Highland Glacier Complex. Spatially variable debris availability offers a potential alternative explanation to the two-phase retreat pattern exhibited in some locations. It is highly probable that LLS glaciers would have reworked large volumes of Lateglacial paraglacial rockslope debris and that this debris contributed to the thick and prominent sequences of recessional hummocky moraine of the LLS (Ballantyne 2002b). In some areas, this supply of debris may have been exhausted mid-way through deglaciation and hence continued active recession was not recorded by moraine formation, giving an apparent or bogus signature of a second phase of uninterrupted retreat.

Also possible is the juxtaposition of valley glaciers experiencing both uninterrupted and active retreat, probably due to localized variations in glacier catchment topography, elevation, aspect, and glacier hypsometry. Bed topography has been shown also to play an important role in both the formation, and preservation, of moraines (Barr & Lovell 2014 and references therein).

Topography probably played a significant role in the lack of moraines along the western lochs of the West Highland Glacier Complex, because they were occupied by marine-terminating, calving glaciers in fjord settings (Bennett 1991). The maximum extents of these glaciers and their recession patterns were probably governed by the topography of their basins, with the ice margins stabilizing and forming moraines only at pinning points (Greene 1992).

An absence of moraines may also be related to the efficient removal of glacial debris at ice margins where glacial and proglacial fluvial systems were well coupled. Here the majority of sediment was removed rapidly from the terminus by meltwater streams, and extensive outwash plains rather than moraines were formed (Benn *et al.* 2003). Such features were not commonly formed by the LLS glaciers in Britain, indicating that proglacial streams were largely inefficient in removing debris from the glacier termini.

#### *Topographic influence on LLS landsystems*

Topography was an important control on glacial landsystem and retreat styles during the LLS, at both regional and local scales. The LLS glaciers had a predominantly small erosive impact on the underlying topography, largely inheriting the recently deglaciated landscape of the Devensian Stage (Evans 2015) and therefore being strongly topographically controlled. In areas dominated by steep slopes and narrow mountain ridges, the gradient of high elevation surfaces was too great to allow sufficient snow accumulation to nourish LLS glaciers and therefore ice was restricted to the lower elevation topography of cirque backwalls and valley heads. These glaciers were nourished by direct snowfall or snow blow and avalanches from neighbouring ridges. Conversely, gently undulating plateaux acted as accumulation areas to feed outlet valley glaciers (Manley 1955, 1959; Rea *et al.* 1998; Rea & Evans 2003).

Topography is also likely to have played a significant role in the earliest, and latest, stages of LLS glaciation. Numerical modelling of the LLS glaciers suggests that ice began to accumulate in the Rannoch Moor area from the beginning of the Stadial (Hubbard 1999; Golledge *et al.* 2008). The high summits of the mountains to the west of the moor would have acted like a snow-fence (Andrews *et al.* 1970; Hulton & Sugden 1997; Golledge 2007, 2008), their high relief facilitating accumulation of large volumes of snow and enabling glacier formation. This relief created first an alpine style of icefield, which then thickened to an icecap that overran all but the highest mountain summits.

Topographic influence was most marked where the cirque glacier landsystem developed, where conditions were just at the threshold for glacierization. The volume of debris in LLS cirque moraines is generally small, indicating that the amount of headwall retreat during the



stadial was low (Evans 2015). Thus, it seems highly probable that the LLS glaciers modified, rather than created, the cirques. North and northeasterly facing cirques were particularly favourable for LLS glacier development, due to maximum protection from insolation, but locations at the margins of upland plateaux or escarpments were also important in terms of snow blow (e.g. Cornish 1981; Mitchell 1996; Bendle & Glasser 2012; Evans 2015).

#### *Palaeoclimatic influence on LLS landsystems*

Notwithstanding the discussion above, the pattern of glacier extent and, therefore, landsystem distribution, was not solely determined by topography. The distribution of LLS glaciers in relation to topography (Fig. 8) reveals that LLS glaciers were sourced in upland areas but numerous locations exist where terrain was above the ELA of the nearest LLS glaciers (often <10 km away), yet remained unglaciated.

Marked regional trends in the ELAs of LLS glaciers are also clear. For example, Ballantyne (2007a) observed a strong linear northward decline in the ELAs of reconstructed LLS glaciers and attributed this to a northwards decline in ablation season temperatures. The warmer ablation season temperatures in southern Britain partly explain why LLS glaciation was limited to cirque and niche glaciers, despite the presence of what were favourable topographic conditions for glaciation. However, a decrease in temperatures driven by latitudinal differences does not account for the presence of various different types of landsystem at the same latitude. A west to east transect across Scotland will intersect a range of landsystems, including the probable transition zone between the Rannoch Moor icecap and the alpine icefield north of the Great Glen, the alpine icefield in the West Drumochter Hills, plateau ice on the Gaick, a high elevation ice-free area around Beinn Iutharn Mhor, and, finally, the cirque glaciers and small alpine and plateau icefields of the southeastern Grampians (Fig. 8).

A LLS precipitation gradient across Scotland (Sissons 1979b, 1980b) is inherent within the numerical modelling of Golledge *et al.* (2008), involving a 60% south–north and an 80% west to east precipitation reduction to the north and east of Rannoch Moor. A further reduction in precipitation from 12.5–12.0 ka BP was imposed, representing a more arid climate during this part of the stadial. Furthermore, as the LLS glaciers expanded to their maximum positions, it is likely that the West Highland Glacier Complex itself exerted increasing influence on the LLS climate, cooling air masses as they passed over the icefield and prompting precipitation (Benn & Ballantyne 2005). Consequently, the climate of the central Highlands was more arid than that of the West Coast, effectively starving the glaciers in this area of precipitation and limiting their size, perhaps explaining why ice masses on the Monadhliath, Gaick and Glen

Mark plateau areas did not evolve into topographically unconfined icecaps. The northwards reduction in precipitation probably contributed to the decrease in thickness of the West Highland Glacier Complex between Rannoch Moor and the area north of the Great Glen, despite cooler temperatures and similar underlying topography.

Calculations of LLS palaeo-precipitation volumes, using the method of Ohmura *et al.* (1992), support the notion of a steep precipitation gradient from west to east across Scotland (e.g. Ballantyne 2002a; Benn & Ballantyne 2005; Lukas & Bradwell 2010). For example, the mean annual precipitation on the Isle of Mull was estimated at 23% higher than at present (Ballantyne 2002a), and at between the present-day value and 25% higher on the Isle of Harris (Ballantyne 2007a). In contrast, the precipitation volumes calculated for inland sites, such as the West Drumochter Hills (Benn & Ballantyne 2005) and Creag Meagaidh (Finlayson 2006) were statistically indistinguishable from present-day values, and those for the Monadhliath were slightly less than modern-day totals.

Increased seasonality, controlled by extensive sea ice, has also been proposed for the LLS climate, and numerical modelling that incorporates greater temperature ranges indicates that both temperature and precipitation were much lower in Scotland than previous empirical-based glacier reconstructions suggested (Golledge *et al.* 2010). Summers were approximately 10 °C cooler than present, but winters may have been up to 30 °C colder (Golledge 2008), probably resulting in a relatively short ablation season. Additionally, glaciers needed less precipitation to remain in climatic equilibrium at their maximum extent. This has necessitated the application of a new temperature-precipitation equation with an added seasonality constant (Golledge *et al.* 2010). For the Skye icefield, this indicates values of: (i) 60–80% of the present-day mean annual precipitation if summer rainfall dominated; (ii) 45–60% for a neutral precipitation regime; and (iii) 35–45% if winter snowfall dominated (Ballantyne *et al.* 2016). For the Monadhliath icefield, the mean annual precipitation values were lower than present-day values, even with a summer precipitation bias (Boston *et al.* 2015). These results concur with regional proxy records indicative of cold and dry LLS winters and hence recalculations of precipitation and temperature values from other LLS glacier reconstructions will be necessary before regional assessments of LLS palaeoclimate can be made.

The nature of the LLS palaeoclimate has important implications for glacier dynamics and retreat patterns. The widespread distribution of recessional hummocky moraine inside the limits of the LLS glaciers throughout much of the northwest Scottish Highlands indicates that these glaciers retreated in an oscillatory fashion, responding to fluctuations in climate, until the later stages of deglaciation. This behaviour is assumed to be driven by



heavy snowfall, with mean annual precipitation totals up to 26% higher than modern-day levels, leading to high mass turnover, rapid responses to climate variations, and the production of dense sequences of recessional moraines (Benn & Lukas 2006).

The LLS palaeoclimate is considered to be a principal control on the two-phase deglaciation pattern observed on the Isle of Skye (Benn *et al.* 1992). The presence of complete early Flandrian pollen sequences from inside the LLS limits in Glen Sligachan and Glen Arroch was used to infer that a significant area had deglaciated before the rapid warming at the end of the stadial (Benn *et al.* 1992). It was suggested that initial deglaciation was active and was driven by reduced accumulation in an arid climate, resulting in extensive recessional moraines. Subsequent rapid warming at the end of the LLS caused uninterrupted retreat (Benn *et al.* 1992). This is in accord with a chironomid-based proxy record of mean summer temperatures from Whitrigg Bog, southeast Scotland, which shows that the coolest temperatures (approximately 7.5 °C) occurred early in the stadial (Brooks & Birks 2000). Temperatures then increased gradually to about 9 °C before increasing rapidly at the transition into the Holocene (Brooks & Birks 2000), a trend also recorded at Abernethy Forest in the central Highlands (Brooks *et al.* 2012). The notion that LLS glacier retreat commenced during the mid-stadial, under gradually warming temperatures, is supported by recalibrated cosmogenic exposure dates in numerous locations throughout Scotland (Ballantyne 2012). However, these ages conflict with radiocarbon dates and varve sequences from the Lomond glacier and Glen Roy, which indicated that ice advance continued until late in the stadial (Palmer *et al.* 2010; MacLeod *et al.* 2011).

This apparent variability in timing of the response of glaciers to changing climate is perhaps to be expected. Glaciers with high elevation source areas may have continued to be nourished whilst those in lowland areas may have become isolated from their accumulation areas and began to downwaste more rapidly (Benn *et al.* 1992). Glaciers with large catchments may have responded more slowly, perhaps accounting for the continued advance of the Roy and Lomond glaciers under a warming climate. Numerical modelling (Golledge *et al.* 2008) driven by a scaled GRIP temperature pattern, and under parameters that were able to closely replicate the extent of LLS glaciation as inferred from the empirical evidence, suggested that the maximum extent of LLS glaciation occurred between 12.6 and 12.4 ka BP. This again supports the notion that, for many of the LLS glaciers, retreat commenced during the mid-stadial under gradually warming temperatures, rather than being triggered by rapid warming at the close of the stadial. This could account for the dominance of active

retreat patterns throughout much of Scotland, with variations in retreat dynamics reflecting the effect of local conditions, such as catchment topography and elevation (including the presence of nearby snow-contributing areas and avalanche prone slopes), glacier size and hypsometry, and microclimate variations.

## Conclusions

- Comprehensive compilation of the glacial geomorphology of the LLS in Britain has facilitated the identification of five landsystem models: (i) cirque/niche glacier landsystem; (ii) alpine icefield landsystem; (iii) lowland piedmont lobe landsystem; (iv) plateau icefield landsystem; and (v) icecap landsystem.
- The landsystems reflect increasing ice thickness and decreasing topographic control on the flow of ice, with the cirque glacier landsystem being typical of localities where conditions were at the threshold of glacierization and hence characterized by the restriction of ice to topographically favourable sites.
- Alpine icefields formed in areas where the underlying topography comprised steep slopes and sharp mountain crests. These glaciers were warm-based, producing sequences of recessional moraines, and were confined to interconnected valleys. In a limited number of locations, outlet glaciers from these icefields formed lowland piedmont lobes when they extended out of the valleys onto more open terrain.
- Plateau icefields developed on gently undulating upland surfaces, which nourished glacier ice and were drained by outlet glaciers. They had complex thermal regimes of both warm- and cold-based ice. The icecap landsystem is present only at the centre of the West Highland Glacier Complex where the geomorphology is strongly indicative of ice flow discordant to the underlying relief, indicating overriding of the topography by a thick icecap.
- Three retreat styles are represented by the glacial geomorphology. These are active retreat throughout deglaciation, two-phased retreat and uninterrupted retreat. The active retreat style appears to be the most widespread and accords well with retreat commencing during the mid-stadial, under gradually warming conditions.
- Retreat style was influenced by a combination of climatic and topographic conditions but the preservation of landforms from which retreat dynamics can be derived also reflects localized variation in debris turnover and availability or the removal of glacial material by proglacial fluvial systems.
- Similarly, the extent and landsystem type of the LLS glaciers were strongly influenced by the interplay of pre-existing topography and climate. The snow-fence effect of the mountains west of Rannoch Moor

combined with the prevailing southwesterly winds allowed accumulations of large volumes of snow that became the centre of the West Highland Glacier Complex. Likewise, cirque glaciers in peripheral locations were able to develop at sites downwind of plateau surfaces, which offered protection from insolation and a source of windblown snow.

- Regional variations in climate also influenced glacier extent and landsystem type. Northward and eastward reductions in precipitation limited the extent of glaciation at more arid sites, but more recent modelling studies suggest that the LLS climate was generally colder, drier and had greater seasonality than previously believed.
- In identifying the type, distribution and possible controls on landsystems associated with the LLS in Britain, this paper provides a regional framework against which modern analogues can be tested to shed greater light on the processes that drove LLS glacial advance and retreat. These landsystem templates also serve as useful boundary conditions for numerical modelling experiments of LLS glaciation and retreat.

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